Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

REVIEW

From Signal to Insight: The Role of Communication Systems in the Remote Sensing Data Value Chain

Yuanfeng Liu

CAAC Central Southern Airport Design & Research Institute (Guangzhou) Co., Ltd., Guangzhou 510405, China

ABSTRACT

High-resolution sensors, satellites in greater numbers, and autonomous flying platforms have ushered in a new era of massive amounts of data, a diversity of modalities, and a sense of urgency in their application due to remote sensing. Although sensing and analytics advances have been extensively investigated, communication systems are taking the broader role in deciding whether remote sensing information can be provided with adequate fidelity, timeliness, and accessibility to create actionable insight. The review uses communication as a value-making part of the remote sensing data value chain, which connects signal acquisition, data transport, processing architectures, and insight generation in an end-to-end view. We combine significant communication architectures of spaceborne, airborne, and hybrid satellite-terrestrial networks, and explain how physical-, link-, and network-layer constraints are passed downstream to affect preprocessing decisions, quality of data products, and real-time utility. The review also looks at the increased integration of communication and computation based on edge and distributed processing, communication-conscious data reduction, and joint optimization schemes that trade off bandwidth, latency, energy, and analytical goals. Lastly, we point to new trends: integrated non-terrestrial networks, software-defined and intelligent communications, and learning-based adaptation; as well as open security, scalability, and interoperability challenges. This article will facilitate clarity in the trade-off in designs and the research focus of creating communication-conscious remote sensing systems by integrating sensing-centric and communications-centric perspectives

*CORRESPONDING AUTHOR:
Yuanfeng Liu, CAAC Central Southern Airport Design & Research Institute (Guangzhou) Co., Ltd., Guangzhou 510405, China;
Email: LYF16@139.com

ARTICLE INFO
Received: 25 February 2026 | Revised: 30 April 2026 | Accepted: 5 May 2026 | Published Online: 12 May 2026
DOI: https://doi.org/10.30564/jees.v8i5.13254

CITATION
Liu, Y., 2026. From Signal to Insight: The Role of Communication Systems in the Remote Sensing Data Value Chain. Journal of Environmental & Earth Sciences. 8(5): 154–168. DOI: https://doi.org/10.30564/jees.v8i5.13254

that will more efficiently transform signals into dependable time-independent insight.

Keywords: Remote Sensing; Non-Terrestrial Networks; Edge Computing; Communication–Computation Co-Design; Data Value Chain

1. Introduction

Remote sensing has emerged as part of the new observation systems that allow the monitoring of the Earth and its environment on a large scale, continuously, and without interruption[1,2]. The development of sensing technologies has gained a great influence in the sensing of phenomena of interest, and has therefore given an enlargement of the range and the resolution of phenomena which are observable; multi-spectral imaging, hyper-spectral imaging, synthetic aperture radar, light detection and ranging, and passive microwave sensing. It is due to these that remote sensing data may now be used in a very broad application, such as in climate change evaluation and catastrophe monitoring, precision farming, urban layout, and national security. Nevertheless, increasing levels of sophistication of the sensing modalities have given rise to a level of data volume, velocity, and heterogeneity that has challenged the very basis of the manner in which the remote sensing data are relayed, processed, and ultimately turned into actionable information[3].

Conventionally, remote sensing research has dealt mostly with sensor design, signal processing, and interpretation of the data without regard to communication systems as an enabling technology. This point of view is becoming inadequate. The contemporary remote sensing systems are not solitary platforms of sensing anymore, but are integrated into elaborate, decentralized systems that traverse space, aerial, and surface space. In this type of system, communication is not just a conveyed medium but a determinant that defines the quality of the data, timeliness, reliability, and usability of the entire lifecycle of the remote sensing data. Therefore, it has become important to find out how communication systems contribute to the remote sensing data value chain in order to maximize the societal and scientific value of sensing data[4,5].

The notion of a data value chain can offer a helpful perspective on the analysis of this end-to-end process. When considering remote sensing, the value chain usually starts with the physical acquisition of the signal, in which the electromagnetic response of the observed object is imprinted on sensors. These uncoded signals should then be sent, typically over large distances and with rigid resource requirements, to ground stations or middle stations. The next steps are the storage of data, preprocessing and fusion, analytics and interpretation, and finally, knowledge extraction and decision making. These chain levels may be potentially value-adding, but they also present constraints and dependencies, most of which are controlled or heavily dependent on the design of communication systems[6].

The communication systems are of particular importance at the interface of sensing and information processing[7]. Bandwidth, latency, energy supplies, and link reliability are limited directly because translating the amount of data that can be sent, the resolution with which it is sent, and the duration thereof are directly affected. A case in point is high-resolution sensors in satellites or unmanned aerial vehicles, which might produce data rates orders of magnitude higher than the available downlink bandwidth; to transmit this data, harsh compression, selective operation, or pre-processing onboard is required. Although such decisions are usually implemented at the communication tier, they have dramatic effects on downstream analytics and the faithfulness of derived products. In this regard, the limitation of communication is effective to influence not just the data flow, but also the insights that can be acquired.

The need to build communication systems is further enhanced by a changing remote sensing network architecture. The increasing use of small satellites, large-scale constellations, and autonomous flying platforms has altered the paradigm of a small number of high-capacity links to highly dynamic, heterogeneous networks. Inter-satellite connections, relay architectures, and hybrid satellite terrestrial networks are also being used to achieve better coverage and latency. Meanwhile, terrestrial communication facilities such as cellular and sensor networks are integrated with remote sensing facilities to facilitate real-time or near-real-time applications. These innovations blur traditional distinctions between the realms of sensing, communication, and computation, which require a systemic and holistic view [8–10].

Simultaneously, the development of data analytics and artificial intelligence has changed the perception of the usefulness of remote sensing data. Instead of using them as the feedstock in offline analysis, remote sensing data are currently supposed to have time-sensitive applications like disaster recovery, environmental management, and smart transportation. To fulfill these expectations, it is necessary that not only effective means of analysis but also communication systems that can provide the relevant data with low latency and high reliability. This has prompted the increased focus on the idea of edge and fog computing, in which part of the data processing is done closer to the sensor to minimize the size of the communication overhead and response time. In this respect, communication design is closely intertwined with computation and analytics, which also enhances its key position in the data value chain [11,12].

In spite of this fact, the current literature tends to cover communication-related issues in a piecemeal fashion, concerning specific technologies, levels, or contexts of application. Though the significance of satellite communication links and airborne networking or data compression techniques has been widely studied alone, fewer studies have been conducted on how the communication systems affect the overall remote sensing data value chain, i.e., signal acquisition to insights generation [13]. Consequently, there are no integrative reviews that provide a compromise between sensing-centric and communication-centric views and express the general implications of communication design options to data value and usability.

This review is intended for remote sensing system architects, researchers, and practitioners who seek to understand how communication constraints propagate through the data value chain from signal acquisition to actionable insight. Communication engineers will find value in the application-oriented analysis of how link-layer decisions affect downstream analytics, while remote sensing specialists will gain awareness of communication limitations often overlooked in sensor-centric designs. The presentation assumes basic familiarity with remote sensing concepts but does not require deep communication theory expertise.

This review tries to fill this gap by offering a holistic end-to-end analysis of the role of communication systems in the remote sensing data value chain. We not only place communication as a central facilitator between sensing, processing, and decision-making but also view it as a complement instead of a subsidiary element. This article aims to identify the main design trade-offs, synergies, and challenges as a result of the analysis of the communication architectures, protocols, and emerging technologies in terms of their effects on the data flow and value creation. Special attention is paid to the way communication limitations and possibilities predetermine data acquisition strategies, the impact of the processing and analytics, and, finally, the quality and timeliness of the insights based on remote sensing data [14].

This review has threefold contributions. The first is that it offers a single conceptual framework for the comprehension of the remote sensing data value chain, where the importance of communication systems at each stage is clearly taken into consideration. Second, it summarizes the recent developments in communication technologies and paradigms related to remote sensing, such as satellite constellations, airborne networks, edge computing, and smart communication strategies. Third, it establishes new trends and research gaps, providing a reflection of future research perspectives of sensing, communication, and data analytics systems co-design [15–17].

The rest of this paper is structured in the following way. Section 2 presents the remote sensing data value chain in an end-to-end view, describing the main steps it consists of and the performance indicators. Section 3 is a review of remote sensing data acquisition and transmission communication systems and architectures. Section 4 explores the use of communication design to facilitate and limit data processing and analytics, and especially computation-conscious and smart methods. Section 5 addresses the new trends and unresolved issues of remote sensing systems based on communication. Lastly, Section 6 summarizes the paper and looks into the future of research.

2. The Remote Sensing Data Value Chain: An End-to-End Perspective

The remote sensing data value chain outlines the series of occurrences wherein the raw physical signals are converted into useful information and actionable knowledge [15]. In contrast to the classic linear data pipelines, this value chain is iterative and connected by nature and has a high dependence between the sensing, communication, computation, and application layers. Communication systems take a key place in this chain, and they mediate the movement of data across stages and essentially define the efficiency, fidelity, and timeliness of value generation. A system-wide view is thus fundamental in the comprehension of how the design decisions at a single point spread out in the system and affect the entire performance. **Figure 1** illustrates this end-to-end remote sensing data value chain and highlights the central role of communication systems in connecting its major stages.

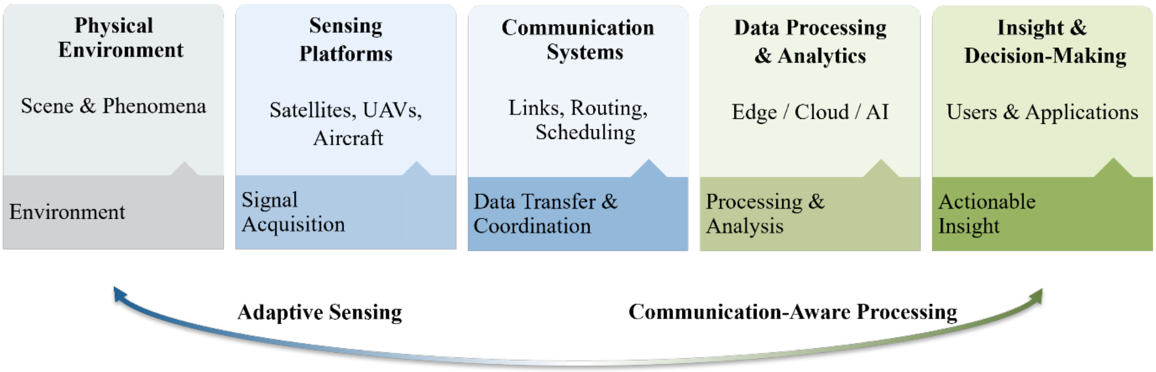

Figure 1. End-to-end remote sensing data value chain.

2.1. Conceptualizing Value in Remote Sensing Data

The definition of value in the context of remote sensing is not based on the raw measurements per se but is formed gradually as the measurements are converted to data, put into context, and interpreted. At the bottom, sensors record electromagnetic radiations which encode data about physical aspects of the scene being observed. These signals have the potential value, but individually, they are normally noisy, redundant, and unavailable to the final users. The information contained in data is enhanced, unpredictability is minimized, and applicability to particular decision situations is enhanced as data flows through the value chain, in terms of transmission, processing, analysis, and dissemination [15,18].

Such a value creation process is limited by technical, economic, and operational factors [19,20]. Restrictions in bandwidth, latency, and reliability of communications may constrain the size of exchanged data and/or introduce a delay in the availability thereof, thus decreasing its effective value. On the contrary, effective communication systems are able to add value through timely delivery, supporting higher data resolutions or even adaptive strategies of acquiring data. In this sense, value should be considered not only a result of sensor ability or the level of analytical complexity, but also the efficiency with which data are transferred and processed through the system.

2.2. Signal Acquisition and Initial Data Generation

The value chain starts with signal acquisition, where remote sensing platforms relate to the environment to acquire data [21]. The range of possibilities of sensing modalities in this stage is large, which comprises optical imaging, radar, lidar, and passive microwave sensing that is spatial, spectral, and even temporal in nature. The development of sensors has greatly enhanced the measurements in terms of resolution and coverage, yet it has resulted in increasing rate of data production at a high rate. Multi-sensor payloads and high-resolution imagers can generate masses of data that are problematic in onboard storage and over the air.

In this infant phase, sensing strategies are already affected by communication concerns [22]. These trade-offs of spatial resolution, temporal frequency, and spectral richness may be necessary due to constraints in transmission capacity. In other instances, sensors may be run in modes that respond to the expected opportunities of communication, like only acquiring high-data-rate when access to downlink is free. This leads to the sensing and communication becoming more and more co-designed instead of independent subsystems.

2.3. Data Transmission and Transport

The most evident use of communication systems in the value chain is data transmission as the interface between data generation and downstream processing. Remote sensing data may have to be relayed over long distances, and/or in adverse propagation conditions, especially in spaceborne and airborne systems. Limited spectrum, power, channel conditions, and intermittent connectivity are such factors that place serious constraints on the throughput and latency that can be achieved[1,23,24].

All these transmission limitations have a direct impact on data stream continuity and completeness. Delays in data transmission can reduce the usefulness of information for real-time uses, whereas the loss of packets or over-compressing can cause a decline in the quality of data. To alleviate these effects, recent remote sensing systems are increasingly using adaptive communication schemes, relay architecture, and prioritization schemes that selectively transmit the most valuable or time-sensitive data. By so doing, the communication layer is also a filter that determines which information continues on the value chain[10,11].

2.4. Data Storage, Processing, and Transformation

After transmission, the remote sensing data is stored, preprocessed, and transformed to stages where raw measurements are processed into calibrated, geo-referenced, and, in many instances, fused data products[25,26]. Such operations can be centralized on the ground, distributed cloud systems, or, with growing popularity, at the intermediate nodes like edge or onboard processors. Connection locality and processing layout are directly connected to communication ones because long-latency or bandwidth constraints of links would render centralized processing unfeasible.

Communication limitations affect the choices that are made concerning the location and manner of processing data[27,28]. More specific to the earlier examples, constraints on downlink data bandwidth can incentivize onboard data preprocessing to eliminate data volume, whereas networks with large data bandwidth can support centralized and data-intensive analytics. These decisions have an impact on system efficiency as well as what kind of algorithms can be implemented and what the granularity of available data products is. Therefore, in order to influence the analytical potential of remote sensing data, communication systems have an indirect but decisive role.

2.5. Information Extraction and Insight Generation

The subsequent phases of the value chain are concentrated on information extraction and the subsequent creation of insights, which aid in supporting scientific knowledge or operational decision-making. This usually entails high-order analytics, such as statistical analysis, data fusion, and machine learning algorithms. The success of such methods is determined by the presence of timely and quality information, and the possibility of reconciling information obtained through various sources[29,30].

The communication systems affect these stages by defining the availability of up-to-date information. In a distributed sensing system (network of satellites, sensor networks, etc.), the data sharing capabilities are realized between different systems and unlock collective processing and enhanced situational awareness[31]. On the other hand, bottlenecks can also disrupt data sets and reduce the extent of analysis. The more real-time or near-real-time insights are expected, in the disaster response application or in the environmental monitoring, the more the communication as the means of maintaining the last stages of the value chain becomes visible.

2.6. Interdependencies and System-Level Considerations

Another characteristic feature of the remote sensing data value chain is that the stages of the chain are highly interdependent. The decision made at either the sensing or the communication layers is propagated through the processing and analytics and affects the final value of the data[32]. The perception of the value chain as a comprehensive system draws attention to the necessity of combined optimization of sensing, communication, and computation, and not the enhancement of separate units.

Based on this end-to-end point of view, communication systems are seen as a unifying factor between physical signal-gathering and high-level generation of insight. Shaping system architecture by controlling data flow, mediating performance measures by trade-offs, and communicating the trade-offs between performance metrics are major functions of the communication design that define the effectiveness of remote sensing systems to convert signals into insight. The latter point of view is what gives the basis for the further analysis of communication architectures and technologies, which is given in the sections below[33]. For clarity, **Table 1** summarizes the major stages of the remote sensing data value chain and the associated roles of communication systems.

Table 1. Representative stages of the remote sensing data value chain and the corresponding roles, constraints, and value contributions of communication systems.

Value Chain Stage	Primary Functions	Role of Communication Systems	Key Constraints
Signal acquisition	Physical measurement of electromagnetic signals	Coordination of sensing schedules; preliminary data formatting	Energy availability; sensing bandwidth
Data transmission	Transfer of raw or preprocessed data	Downlink/uplink scheduling; adaptive rate control	Limited bandwidth; link intermittency
Data storage	Temporary or long-term data retention	Data routing to storage nodes	Latency; storage-access throughput
Data processing	Calibration, correction, fusion	Support for distributed or centralized processing	Communication–computation coupling
Analytics and interpretation	Feature extraction and inference	Timely delivery of analytics inputs	Delay sensitivity
Information dissemination	Delivery to end users	Reliable and prioritized information transfer	Quality-of-service guarantees

3. Communication Systems for Remote Sensing Data Acquisition and Transmission

Operation backbone Communications systems are what enable remote sensing platforms be able to provide data even after acquisition[4]. With the development of sensing technologies of increased resolutions, more compact temporal sampling, and integration of multiple sensors, there has been an increase in the requirements of the communication subsystems. In contemporary remote sensing systems, communication is not a passive data delivery vehicle, but rather an active element of the system that determines sensing strategies and network structures, and system performance. Here, remote sensing data acquisition and transmission communication systems are analyzed in terms of architecture and functionality with a focus on how their functionality fits in the wider data value chain.

3.1. Communication Architectures in Remote Sensing Systems

The remote sensing platforms are deployed in various environments that include, but are not limited to, deep space and low Earth orbit, the atmosphere, and on the ground. The architecture of communications, therefore, has to support heterogeneous linkage attributes and installation limitations. Traditionally, space systems have been based on direct downlinks with ground stations, with possible additions of relay satellites to enhance coverage and minimize latency. The advent of large constellations of satellites has brought additional complex designs that use inter-satellite connections to be able to route and aggregate data in space prior to being transmitted to the ground[13,34].

Aerial and unmanned aerial platforms offer a varying architectural framework, which is highly mobile and possesses comparatively smaller communication vicinities[35]. These networks tend to take advantage of line-of-sight connections with ground stations or create ad hoc networks to share data with each other. Hybrid architectures that combine satellite, aerial, and terrestrial communication infrastructures are gaining considerable use in order to enable coverage continuity and adaptable data routing. These types of architecture will dissolve the line between sensing and networking and will turn remote sensing platforms into active nodes in the larger structures of communication.

3.2. Physical and Link Layer Considerations

The remote sensing communication systems are highly constrained at the physical layer and link layer, unlike traditional communication networks. Onboard power is limited, spectrum sharing is limited, and propagation environments are challenging, so strict constraints exist on the data rates and link reliability that can be achieved. Atmospheric attenuation, Doppler effects, and interference are also additional issues that complicate the design of links, especially at high-frequency and high-throughput systems[7,36].

Such limitations require the application of powerful modulation, coding, and adaptive transmission methods.

Link adaptation schemes that are used to adapt the data rate, coding scheme, or transmission schedule to channel conditions are commonly used to achieve maximum throughput whilst ensuring reliability[37]. Value chain-wise, these low-level design decisions have a direct impact on data integrity and completeness, which in turn impact the quality of the downstream processing and analysis.

3.3. Managing Data Volume and Throughput Constraints

The issue of the rate of data generation versus the transmission capacity is one of the biggest issues of remote sensing communication[19]. The progressive increase of sensor resolution and sampling frequency has exceeded of communication bandwidth and offers a continuing bottleneck in the value chain. This asymmetry compels system designers to make partial choices regarding what data to send, when to send it, and with what level of fidelity.

To overcome these issues, communication systems are now implementing more intimate data-conscious mechanisms over and above mere bit transport[38]. It is achieved by compression, priority, and selective retransmission techniques in order to provide the most information-preserving data or time-sensitive data in the first place. Sensing operations themselves are, in other cases, adapted according to the expected communication constraints, which further supports the close interaction between data acquisition and transmission. Such strategies indicate the change from maximization of raw throughput to maximization of delivered data value.

3.4. Network-Level Coordination and Data Routing

Network-level coordination is a major issue in the transmission of data as remote sensing systems are developed into distributed and networked architectures. In satellite constellations, multi-platform sensing networks, data, in many cases, have to be sent through various hops before it arrives at processing centers. The availability of links, node mobility, and energy constraints are the factors that are used in routing decisions, and they are dynamic in nature and change with time[39].

The efficiency and resilience of the data value chain can be boosted considerably because of efficient coordination on the network level[40]. Communication systems can overcome link constraints associated with individual links and lower end-to-end latency by using alternative paths or through cooperative relaying. These benefits are, however, at the expense of more system complexity and the overhead of coordination. The resulting trade-offs demonstrate the significance of network-conscious communication design in the need to maintain scalable and dependable remote sensing operations. **Table 2** compares representative communication architectures across different remote sensing platforms.

Table 2. Comparison of communication architectures used in spaceborne, airborne, terrestrial, and hybrid remote sensing platforms, highlighting their advantages and limitations.

Platform Type	Communication Architecture	Typical Links	Advantages	Limitations
Spaceborne (single satellite)	Direct-to-ground	Space–ground	Simple architecture; mature technology	Limited coverage; high latency
Satellite constellations	Inter-satellite + ground relay	Space–space; space–ground	Low latency; global coverage	High coordination complexity
Airborne platforms	Line-of-sight and ad hoc networking	Air–ground; air–air	Flexible deployment; high data rates	Limited endurance
Hybrid systems	Integrated satellite–aerial–terrestrial	Multi-domain	Resilient and scalable	Interoperability challenges

3.5. Reliability, Latency, and Timeliness of Data Delivery

In addition to the raw data rates, communication systems are also evaluated by their capability of delivering data in a reliable and acceptable amount of time. In most remote sensing applications, especially in the monitoring and response applications, the usefulness of the data decays quickly with time. Latency at the communication stage can therefore bring down the usefulness of otherwise good data[7].

Communication system design is linked with reliability and timeliness[41]. Delay, data integrity, and all are affected by error control mechanisms, retransmission strategies, and buffering policies. The key challenge is to design communication systems that are both reliable and have minimal latency, and this is more so in environments where connectivity is intermittent. End-to-end, such a balance is needed in order to maintain the value created in the sensing process and allow proper downstream decision-making.

3.6. Implications for End-to-End System Design

The above discussion highlights the fact that remote sensing data acquisition and transmission communication systems cannot be developed in isolation. Through architectural design, physical-layer methods, and network protocols, how data is transported through the value chain and the level of value that is eventually achieved are all established. The communication constraints are used to design sensing strategies, shape processing architectures, and determine the viability of advanced analytics [42].

The realization of such interdependencies leads to a desire to move toward sensing goal and application requirement-specific, integrated, and adaptable communication designs. This kind of strategy prepares the pathway to closer marriages between communication, computation, and intelligence, as discussed in the following section. Remote sensing systems can be optimally designed to transform signals into insight by considering communication as a value-forming part and not as a transport layer [11,43].

4. Enabling Data Processing and Analytics through Communication Design

Converting remote sensing data into actionable insight is only possible not only by sophisticated analytical techniques but also by communication systems encompassing the movement and coordination of data through processing phases. With the growth in the volume of data and the time sensitivity of the applications, the communication design is becoming the determinant of where, when, and how data processing and analytics are done. Instead of merely acting as a channel between sensing and centralized processing resources, communication systems play an active role in developing computational architectures and analysis processes in the remote sensing data value chain [44,45].

4.1. Communication Constraints and Their Impact on Data Processing

In remote sensing systems, communication constraints can put major constraints on data processing strategies. Limited bandwidth, intermittent connectivity, and latency that cannot be totally ignored can render transmitting all raw sensor data to central facilities impractical so as to perform analysis. Consequently, the processing architectures have to be adapted to the nature of communication links between sensing platforms and intermediate nodes, as well as end users [46].

Such limitations affect the choices of the extent of preprocessing onboard sensors, the choice of data representations, and when processing will occur. As an example, limited downlink opportunities can be managed by processing or summarizing raw data before transmission, thus decreasing the size of the data at the expense of a certain amount of information loss. On the other hand, low-latency and high-capacity links allow more centralized and more data-driven processing methods. By so doing, the analytical fidelity and flexibility of remote sensing applications are indirectly dependent on the communication systems [47,48].

4.2. Distributed Processing and Edge-Oriented Architectures

In a bid to reduce the communication bottleneck and enhance responsiveness, remote sensing systems are increasingly being implemented using a distributed processing paradigm [49,50]. The edge and fog computing architectures place a part of the processing load nearer to the data source to allow the analysis and decision-making to occur early, before the data is sent through the limited links. Communication systems can be considered very important in facilitating such architectures, to coordinate data transfer between the distributed processing nodes, and also to control the stream of intermediate results.

In edge-oriented designs, communication is not just about the transmission of raw data but also about communication to synchronize, offload tasks, and control. The performance of such interactions not only influences the processing latency, but also the energy use and scalability of the system in general. Communication protocols can be adapted to a distributed processing mode by means of tailoring and, and when so, remote sensing systems can achieve more balanced trade-offs between computational load and communication overhead, making the overall value chain more efficient[51,52].

4.3. Communication-Aware Data Reduction and Fusion

This involves data compression, feature extraction, and data fusion, which are associated with the management of the size of modern remote sensing data. Although considered to be processing-layer functions, the techniques are now often developed with a conscious understanding of communication constraints. The communication-aware data reduction is designed in such a way that it maintains the most informative bit of the data and thus lowers the transmission needs, therefore maximizing the value delivered given the limited resources[53].

The interplay between communication and analytics can also be further demonstrated when there is data fusion between two or more sensors or platforms[54]. The fusion may demand more out of communication systems since effective fusion may need the exchange of intermediate data products or metadata. In the case of scarce communication resources, fusion strategies can be configured to be hierarchical or opportunistic with partial or delayed information. These adaptations highlight the importance of communication design on the viability as well as the architecture of sophisticated analysis techniques.

4.4. Joint Optimization of Communication and Computation

The increasing interdependence of communication and processing has been driving the study of joint optimization structures that look at both facets simultaneously. In place of maximizing either communication throughput or computational efficiency individually, these strategies aim at balancing resource utilization within the system to meet application-level goals, including the minimization of end-to-end latency or information gain[24].

Joint communication-computation optimization can be applied in remote sensing applications, where dynamically allocating bandwidth or processing tasks or changing sensing parameters can be performed depending on system state and application priorities[55]. Such adaptive behavior requires communication systems that provide the feedback and control channels required to support such adaptive behavior. Communication design is a major facilitator of smart and reactive remote sensing analytics due to the ability to coordinate the management of resources. The role of communication-aware mechanisms in shaping data flow toward insight generation is summarized in **Figure 2**.

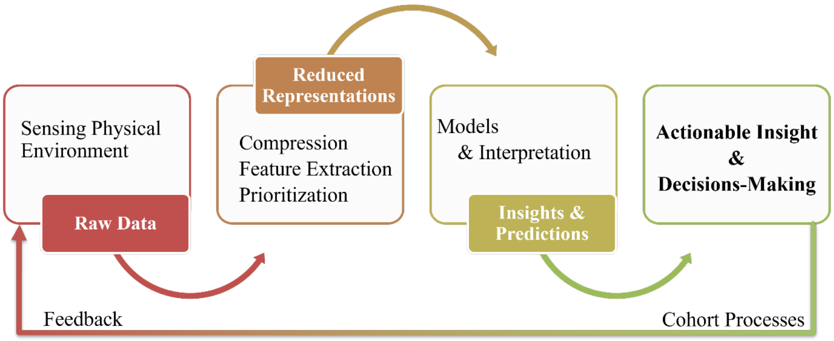

Figure 2. Communication-aware data flow in the remote sensing value chain.

4.5. The Role of Intelligent and Learning-Based Communication Strategies

Machine learning and artificial intelligence have started to affect the design of communication systems, even more intensifying the connection between communication and analytics[56,57]. Communication strategies that are grounded in learning are able to modify transmission policies, routing choices, and schemes of data prioritization depending on evaluated system performance and environmental circumstances. In remote sensing systems, it can be used in a way that allows communication behavior to be unified with analytical goals, e.g., to focus on the data that is important to the observed events or emergent patterns.

Intelligent communication mechanisms bring new opportunities and challenges in light of their integration. Although adaptive and predictive approaches can enhance efficiency and responsiveness, they also bring a rise in the complexity of systems and necessitate effective sharing of contextual information. The communication systems are then required to facilitate the data transfer in addition to the spread of models, parameters, and control information that form the basis of intelligent analytics[58].

4.6. Implications for Insight Generation and System Evolution

Communication design is decisive in converting remote sensing data into insight by the way that it influences processing architectures, facilitating distributed analytics, and providing intelligent adaptation[44]. The usefulness of analytical tools cannot be used outside of a communication infrastructure that supports them, especially with large-scale and time-sensitive applications.

This interdependence can be significant to the future development of remote sensing systems[11]. Communication systems can be designed with clear regard to the processing and analytics needs to unlock higher degrees of performance and dynamism, enabling remote sensing systems to operate in dynamic ways based on the needs and conditions. The latter view preconditions the discussion of emerging tendencies and unresolved issues in remote sensing systems based on communication, which are presented in the following section. The relationship between communication constraints and processing strategies is summarized in **Table 3**.

Table 3. Impact of key communication constraints on data processing and analytics strategies in remote sensing systems, along with common mitigation approaches.

Communication Constraint	Processing Implications	Typical Mitigation Strategy
Limited bandwidth	Reduced data fidelity	Compression; feature extraction
High latency	Delayed analytics	Edge processing
Intermittent connectivity	Incomplete data streams	Opportunistic transmission
Energy constraints	Limited onboard processing	Adaptive task offloading
Network congestion	Processing backlogs	Priority-based data scheduling

5. Emerging Trends and Open Challenges in the Communication-Driven Value Chain

The high rate of development of remote sensing systems is transforming the position of communication in the data value chain[11]. The growth of system scale, more restrictive performance requirements, and increased integration with smart analytics is simultaneously driving the application of new communication paradigms and, in the process, revealing unresolved technical and conceptual problems. The need to know these new trends and open issues is critical in informing future research, as well as in ensuring that communication systems remain useful in ensuring that remote sensing data is still converted into insight.

5.1. Integration of Next-Generation and Non-Terrestrial Networks

In remote sensing, next-generation communication technologies are finding their way more and more often into infrastructures. The integration between terrestrial networks and non-terrestrial elements, such as satellites and air platforms, allows more adaptable and reliable routes for delivering data. These combined networks enable information interchange among spaceborne, airborne, and terrestrial systems, which diminishes the cost and enhances space sensing to distant areas[59].

Nonetheless, with this integration, there are new challenges of interoperability, network management, and performance assurance. The diversity of link characteristics, the mobility variation, and the different quality-of-service needs make it difficult to design unified communication structures. Achieving the ability of remote sensing data to travel across such integrated networks without fidelity and timeliness is an unsolved problem, especially with the ever-increasing complexity of systems[60].

5.2. Intelligent and Software-Defined Communication Systems

The use of soft-defined and virtualized communication architectures constitutes a point of significant change in the way remote sensing communication systems are designed and run[61]. These techniques permit the dynamically varying communication behavior of the network to both sensing and processing requirements by decoupling control and data planes, as well as providing programmable network functionality. In the application of remote sensing systems, the flexibility can facilitate context-sensitive transmission schemes and quick reconfiguration to adapt to the evolving mission requirements or environmental factors.

Simultaneously, the growing dependence on software control raises the issue of robustness, latency, and verification of the system[62]. Software-defined communication systems have to survive well in resource-constrained and sometimes harsh environments, failure of which may cause an entire break in the whole data value chain. One of the research challenges is in developing architectures that are flexible, predictable, and resilient.

5.3. Security, Privacy, and Resilience Considerations

With the growing connectivity and data-driven nature of remote sensing systems, the issue of security and privacy has become more prominent[63]. The main target of possible attacks, information breaches, or interruptions is communication systems, and hence they should be the top priority when deciding on the integrity of the value chain. Unauthorized users who have access to sensing data, manipulate transmitted information, or conduct denial-of-service attacks may undermine the quality of data and confidence in insights obtained.

Power, computation, and bandwidth limits make it difficult to ensure secure and resilient communications in remote sensing scenarios. The conventional security systems can be too resource-demanding, and the lightweight ones can have restricted security. Striking a balance between security requirements and performance constraints on the one hand, and considering security in communication and processing co-design on the other hand, is an open and immediate challenge[19].

5.4. Scalability for Large-Scale and Dense Sensing Networks

Scalability of communication is being put to unprecedented challenges by the trend toward big constellations of satellites and dense sensing deployments[64]. The larger the number of sensing nodes, the larger the amount of generated data, as well as the complexity of coordination needed to handle data flows. Communication systems should be able to increase these demands without being a value chain choke point.

Scalability issues at each of the levels, such as spectrum utilization, network coordination, and control overhead, are present. Scalable distribution of communication resources among many nodes demands sophisticated access and scheduling schemes, and decentralized control schemes or hierarchical schemes. Such challenges are to be addressed in order to achieve the full potential of next-generation remote sensing systems.

5.5. Standardization and Interoperability Gaps

Although technological advancement has been at a very high rate, not all areas that have experienced innovation in remote sensing communication systems have been standardized. Varying platforms, vendors, and application spaces tend to use proprietary or poorly coordinated solutions, which make interoperability and sustainability difficult. The absence of widely used standards also makes data sharing, system integration, and collaborative processing across organizational and national boundaries more complicated.

To resolve these standardization gaps, there must be efforts by the remote sensing, communication, and data analytics communities to coordinate their activities. The standards of communication that explicitly take into consideration the needs of remote sensing data and applications can help ensure closer integration and minimize redundancy of effort. Nevertheless, it is still a challenge to agree in the fast-changing technology world[65].

5.6. Outlook on Research Directions and System Evolution

The trends and challenges mentioned above are pointing to the future, whereby communication systems are integrated into an intelligent and adaptive remote sensing infrastructure. The use of interdisciplinary research, including sensing, communication, and computation, will be needed to address the open challenges associated with incorporating integration, intelligence, security, scalability, and standardization[66].

In view of the value chain perspective, future communication systems have to be configured to transfer data effectively and fulfill the growing analytical and decision-making requirements[67]. Through the use of holistic and proactive methods, the research community can assist in making sure that communication-based innovations remain useful in increasing the capacity of remote sensing systems to transform signals into useful and timely insight. **Table 4** summarizes the key emerging trends and open challenges discussed in this section.

Table 4. Emerging trends and open challenges in communication-driven remote sensing systems, with implications for scalability, security, and interoperability.

Trend	Description	Associated Challenges
Integrated non-terrestrial networks	Unified satellite–aerial–terrestrial communications	Network management complexity
Software-defined communications	Programmable and adaptive networking	Reliability and validation
Intelligent communication control	Learning-based adaptation	Model robustness and overhead
Large-scale sensing networks	Dense satellite and sensor deployments	Scalability and spectrum sharing
Standardization efforts	Interoperable communication frameworks	Cross-domain consensus

6. Conclusions

This review has discussed the functions of communication systems as a key value-forming and central platform of the remote sensing data value chain. With the trends in the development of remote sensing platforms towards finer resolution, increasing autonomy, and wider spatial and temporal scale, the communication, coordination, and management of data across the system becomes increasingly important to the potential to transform raw signals into useful insight. Communication systems, as opposed to being just a medium of transmission, impact all phases of the value chain, including sensing strategies and information gathering, data processing architectures, and ultimate decision support.

This article has identified the interdependencies among senses, communication, and analytics by taking an end-to-end approach. Limits of communication, like bandwidth, latency, reliability, and access to energy, have a direct impact on data fidelity, timeliness, and accessibility and may influence the kind of insights that can be obtained in the end. Simultaneously, the development of communication architectures, adaptive transmission techniques, and coordination on the network level creates fresh possibilities to address these limitations and add overall value to the remote sensing data. Being aware of these trade-offs is critical to the design of systems that can perform effectively with an ever-increasing number of demands.

The convergence in communication and computation in remote sensing systems has also been highlighted in the review. Distributed and edge-based processing models, communication-aware data reduction, and combined organization of communication and computation resources depict how communication design is increasingly being tightly integrated with analytical processes. This intersection facilitates more responsive and scalable systems as well as creates new complexity that needs to be addressed using smart and adaptive design methods.

Other trends are emerging that combine terrestrial and non-terrestrial networks, software-defined communication systems, and learning-based adaptation, which are also supporting the strategic value of communication as part of the data value chain. Meanwhile, the presence of open issues and concerns such as security, privacy, scalability, and standardization underlines that further research and interdisciplinary cooperation should be maintained. These challenges would be important in solving the issues of robustness, interoperability, and long-term sustainability of future remote sensing infrastructures.

Finally, communication systems are a fact that will dictate the effectiveness of remote sensing information in converting the signal to wisdom. The understanding of communication as a fundamental enabler and not an adjunct element gives a basis for more holistic system design and places more emphasis on the integration of sensing, communication, and intelligence. Future studies that adopt this combined approach will play a central role in realizing the full promise of remote sensing in solving scientific, environmental, and social problems.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or generated in this study. All data is presented in the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Dash, J., Ogutu, B.O., 2016. Recent advances in spaceborne optical remote sensing systems for monitoring global terrestrial ecosystems. Progress in Physical Geography. 40(2), 322–351.

[2] Chuvieco, E., 2008. Earth Observation of Global Change: The Role of Satellite Remote Sensing in Monitoring the Global Environment. Springer: Dordrecht, The Netherlands.

[3] Dalla Mura, M., Prasad, S., Pacifici, E., et al., 2015. Challenges and opportunities of multimodality and data fusion in remote sensing. Proceedings of the IEEE. 103(9), 1585–1601.

[4] Toth, C., Jóźków, G., 2016. Remote sensing platforms and sensors: A survey. ISPRS: International Society for Journal of Photogrammetry and Remote Sensing. 115, 22–36.

[5] Barsi, Á., Kugler, Z., Juhász, A., et al., 2019. Remote sensing data quality model: From data sources to lifecycle phases. International Journal of Image and Data Fusion. 10(4), 280–299.

[6] Olla, P., Patel, N.V., 2002. A value chain model for mobile data service providers. Telecommunications Policy. 26(9–10), 551–571.

[7] Ma, Z., Xiao, M., Xiao, Y., et al., 2019. High-reliability and low-latency wireless communication for internet of things: Challenges, fundamentals, and enabling technologies. IEEE Internet of Things Journal. 6(5), 7946–7970.

[8] Burleigh, S.C., Cola, T.D., Morosi, S., et al., 2019. From connectivity to advanced internet services: A comprehensive review of small satellites communications and networks. Wireless Communications and Mobile Computing. 2019(1), 6243505.

[9] Wang, P., Zhang, J., Zhang, X., et al., 2019. Convergence of satellite and terrestrial networks: A comprehensive survey. IEEE Access. 8, 5550–5588.

[10] Zhang, P., Qin, Q., Zhang, S., et al., 2024. Near realtime remote sensing based on satellite internet: Architectures, key techniques, and experimental progress. Aerospace. 11(2), 167.

[11] Zhang, B., Wu, Y., Zhao, B., et al., 2022. Progress and challenges in intelligent remote sensing satellite systems. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 15, 1814–1822.

[12] Feng, D., Lai, L., Luo, J., et al., 2021. Ultra-reliable and low-latency communications: Applications, opportunities and challenges. Science China Information Sciences. 64(2), 120301.

[13] Hui, M., Zhai, S., Wang, D., et al., 2025. A review of LEO satellite communication payloads for integrated communication, navigation, and remote sensing: Opportunities, challenges, future directions. IEEE Internet of Things Journal. 12 (12), 18954–18992.

[14] Drake, D.A., Quist, G.M., 2007. Remote sensing and communication system. US7292143B2. 16 November 2007.

[15] Siddiqi, A., Baber, S., de Weck, O., et al., 2020. Error and uncertainty in earth observation value chains. In Proceedings of IGARSS 2020 IEEE International Geoscience and Remote Sensing Symposium, Waikoloa, HI, USA, 26 September–2 October 2020; pp. 3158–3161.

[16] Kumar, G.K., Sankar, P., 2025. Artificial intelligence powered satellite communications and Sentinel satellite constellations: An overview and future perspectives. SN Computer Science. 6(6), 735.

[17] Zhao, G., Imran, M.A., Pang, Z., et al., 2018. Toward real-time control in future wireless networks: Communication-control co-design. IEEE Communications Magazine. 57(2), 138–144.

[18] Sabins Jr., F.F., Ellis, J.M., 2020. Remote Sensing: Principles, Interpretation, and Applications, 4th ed. Waveland Press: Lake Zurich, IL, USA.

[19] Chi, M., Plaza, A. Benediktsson, J.A., et al., 2016. Big data for remote sensing: Challenges and opportunities. Proceedings of the IEEE. 104(11), 2207–2219.

[20] Khanal, S., Kushal, K.C., Fulton, J. P., et al., 2020. Remote sensing in agriculture—Accomplishments, limitations, and opportunities. Remote Sensing. 12(22), 3783.

[21] Navalgund, R., Jayaraman, V., Kumar, A.S.K., et al.,

1996. Remote sensing data acquisition, platforms and sensor requirements. Journal of the Indian Society of Remote Sensing. 24(4), 207–237.

[22] Sapsanis, C., Sophocleous, M.A., Andreou, A.G., et al., 2022. Trade-offs in sensor systems design: A tutorial. IEEE Sensors Journal. 22(11), 10040–10061.

[23] Milani, L., 2019. Atmospheric Remote Sensing and Radiopropagation: From Numerical Modeling to Spaceborne and Terrestrial Applications [PhD Thesis]. Università degli Studi di Roma La Sapienza: Rome, Italy.

[24] Lee, C.A., Gasster, S.D., Plaza, A., et al., 2011. Recent developments in high performance computing for remote sensing: A review. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 4(3), 508–527.

[25] Patanè, G., Spagnuolo, M. (Eds.), 2016. Heterogeneous Spatial Data: Fusion, Modeling, and Analysis for GIS Applications. Morgan & Claypool Publishers: Cham, Switzerland.

[26] Al Mamun, M., Jia, X., Ryan, M., 2009. Adaptive data compression for efficient sequential transmission and change updating of remote sensing images. In Proceedings of 2009 IEEE International Geoscience and Remote Sensing Symposium, Cape Town, South Africa, 12–17 July 2009.

[27] Zhu, C., Shu, L., Hara, T., et al., 2014. A survey on communication and data management issues in mobile sensor networks. Wireless Communications and Mobile Computing. 14(1), 19–36.

[28] Dai, H.-N., Wong, R.C.-W., Wang, H., et al., 2019. Big data analytics for large-scale wireless networks: Challenges and opportunities. ACM Computing Surveys. 52(5), 1–36.

[29] Zhang, Z., Zhu, L., 2023. A review on unmanned aerial vehicle remote sensing: Platforms, sensors, data processing methods, and applications. Drones. 7(6), 398.

[30] Liang, S., Wang, J. (Eds.), 2019. Advanced Remote Sensing: Terrestrial Information Extraction and Applications. Academic Press: Cambridge, MA, USA.

[31] Ehala, J., Kaugerand J, Pahtma R, et al., 2017. Situation awareness via Internet of things and in-network data processing. International Journal of Distributed Sensor Networks. 13(1), 95–100. DOI: https://doi.org/10.1177/1550147716686578

[32] Zhao, F., Guibas, L.J., 2004. Wireless Sensor Networks: An Information Processing Approach. Morgan Kaufmann: San Francisco, CA, USA.

[33] Xu, Y., Chen, X., Ying, M., et al., 2025. Integrated communication and remote sensing in LEO satellite systems: Protocol, architecture and prototype. IEEE Transactions on Wireless Communications. 25, 1609–1623.

[34] Davarian, F., Asmar, S., Angert, M., et al., 2020. Improving small satellite communications and tracking in deep space—A review of the existing systems and technologies with recommendations for improvement. Part II: Small Satellite Navigation, Proximity Links, and Communications Link Science. IEEE Aerospace and Electronic Systems Magazine. 35(7), 26–40.

[35] Jawhar, I., Mohamed, N., Al-Jaroodi, J., et al., 2017. Communication and networking of UAV-based systems: Classification and associated architectures. Journal of Network and Computer Applications. 84, 93–108.

[36] Ippolito Jr., L.J., 2017. Satellite Communications Systems Engineering: Atmospheric Effects, Satellite Link Design and System Performance. John Wiley & Sons: Chichester, UK.

[37] Caponi, L., Chiti, F., Fantacci, R., 2007. Performance evaluation of a link adaptation technique for high speed wireless communication systems. IEEE Transactions on Wireless Communications. 6(12), 4568–4575.

[38] Dhabliya, D., Soundararajan, R., Selvarasu, P., et al., 2022. Energy-efficient network protocols and resilient data transmission schemes for wireless sensor networks—An experimental survey. Energies. 15(23), 8883.

[39] Vijay, Siddiqui, S.T., Ritu, et al., 2022. Intertwine connection-based routing path selection for data transmission in mobile cellular networks and wireless sensor networks. Wireless Communications and Mobile Computing. 2022(1), 8398128.

[40] Yang, J., Li, D., Jiang, X., et al., 2020. Enhancing the resilience of low earth orbit remote sensing satellite networks. IEEE Network. 34(4), 304–311.

[41] Al Mamun, M.A., Li, M., Pramanik, B.K., 2024. Development of delay-tolerant networking protocols for reliable data transmission in space networks: A simulation-based approach. IEEE Access. 12, 36677.

[42] Ganesan, D., Estrin, D., Heidemann, J., 2003. Dimensions: Why do we need a new data handling architecture for sensor networks? ACM Sigcomm Computer Communication Review. 33(1), 143–148.

[43] Rohith, G., Sutha, G.L., 2022. Super-Resolution for Remote Sensing Applications Using Deep Learning Techniques. Cambridge Scholars Publishing: Necastle upon Tyne, UK.

[44] Dritsas, E., Trigka, M., 2025. Remote sensing and geospatial analysis in the big data era: A survey. Remote Sensing. 17(3), 550.

[45] Ahmad, R., 2024. Smart remote sensing network for disaster management: An overview. Telecommunication Systems. 87(1), 213–237.

[46] Shen, C.-C., Srisathapornphat, C., Jaikaeo, C., 2001. Sensor information networking architecture and applications. IEEE Personal Communications. 8(4), 52–59.

[47] Lippitt, C.D., Stow, D.A., Riggan, P.J., 2016. Application of the remote-sensing communication model to a time-sensitive wildfire remote-sensing system. International Journal of Remote Sensing. 37(14), 3272–3292.

[48] Franconi, N., Sabogal, S., George, A., et al., 2020. A

novel RF Architecture for Simultaneous Communication, Navigation, and Remote Sensing with Software-Defined Radio. In Proceedings of the 34th Annual Conference on Small Satellites, Logan, UT, USA, 3–8 August 2020.

[49] Wu, Z., Sun, J., Zhang, Y., et al., 2021. Recent developments in parallel and distributed computing for remotely sensed big data processing. Proceedings of the IEEE. 109(8), 1282–1305.

[50] Zhang, Q., Xu, L., Huang, J., et al., 2025. Distributed satellite information networks: Architecture, enabling technologies, and trends. Science China Information Sciences. 68(9), 190301.

[51] Yang, A., Liu, J., Yang, B., et al., 2025. Balancing communication overhead and accuracy in compression integration: A survey. The Journal of Supercomputing. 81(8), 964.

[52] Ballotta, L., Schenato, L., Carlone, L., 2020. Computation-communication trade-offs and sensor selection in real-time estimation for processing networks. IEEE Transactions on Network Science and Engineering. 7(4), 2952–2965.

[53] Park, J., Samarakoon, S., Elgabli, A., et al., 2021. Communication-efficient and distributed learning over wireless networks: Principles and applications. Proceedings of the IEEE. 109(5), 796–819.

[54] Fortino, G., Galzarano, S., Gravina, R., et al., 2015. A framework for collaborative computing and multi-sensor data fusion in body sensor networks. Information Fusion. 22, 50–70.

[55] He, Y., Yu, G., Luo, H., et al., 2023. Integrated sensing, computation, and communication: System framework and performance optimization. IEEE Transactions on Wireless Communications. 23(2), 1114–1128.

[56] Kibria, M.G., Nguyen, K., Villardi, G.P., et al., 2018. Big data analytics, machine learning, and artificial intelligence in next-generation wireless networks. IEEE Access. 6, 32328–32338.

[57] Ahmad, I., Shahabuddin, S., Malik, H., et al., 2020. Machine learning meets communication networks: Current trends and future challenges. IEEE Access. 8, 223418–223460.

[58] Iqbal, R., Doctor, F., More, B., et al., 2020. Big data analytics and computational intelligence for cyber–physical systems: Recent trends and state of the art applications. Future Generation Computer Systems. 105, 766–778.

[59] Matera, F., Settembre, M., Rago, A., et al., 2024. Terrestrial and non-terrestrial networks for integrated sensing and communication. In Proceedings of 2024 IEEE International Symposium on Systems Engineering (ISSE), Perugia, Italy, 16–19 October 2024; pp. 1–5.

[60] Geraci, G., López-Pérez, D., Benzaghta, M., et al., 2022. Integrating terrestrial and non-terrestrial networks: 3D opportunities and challenges. IEEE Communications Magazine. 61(4), 42–48.

[61] Xu, S., Wang, X.-W., Huang, M., 2018. Software-defined next-generation satellite networks: Architecture, challenges, and solutions. IEEE Access. 6, 4027–4041.

[62] Baillieul, J., Antsaklis, P.J., 2007. Control and communication challenges in networked real-time systems. Proceedings of the IEEE. 95(1), 9–28.

[63] Zhang, D., Ren, L., Shafiq, M., et al., 2022. A lightweight privacy-preserving system for the security of remote sensing images on IoT. Remote Sensing. 14(24), 6371.

[64] Kodheli, O., Lagunas, E., Maturo, N., et al., 2020. Satellite communications in the new space era: A survey and future challenges. IEEE Communications Surveys & Tutorials. 23(1), 70–109.

[65] Koufos, K., EI Haloui, K., Dianati, M., et al., 2021. Trends in intelligent communication systems: Review of standards, major research projects, and identification of research gaps. Journal of Sensor and Actuator Networks. 10(4), 60.

[66] Wang, J., Varshney, N., Gentile, C., et al., 2022. Integrated sensing and communication: Enabling techniques, applications, tools and data sets, standardization, and future directions. IEEE Internet of Things Journal. 9(23), 23416–23440.

[67] Rathore, M.M.U., Paul, A., Ahmad, A., et al., 2015. Real-time big data analytical architecture for remote sensing application. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 8(10), 4610–4621.